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# Undergraduate Measurements of Neutron Cross Sections

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**Abstract**

Undergraduate students at the University of Dallas have investigated basic properties of nuclei through γ-ray and neutron spectroscopy following neutron scattering. The former has been used primarily for nuclear structure investigations, while the latter has been used to measure neutron scattering cross sections important for fission reactor applications. A series of $(n,n')$ and $(n,n'\gamma)$ measurements have been made on $^{54}$Fe and $^{56}$Fe to determine neutron cross sections for scattering to excited levels in these nuclei. The former provides the cross sections directly and the latter are used to deduce inelastic neutron scattering cross sections by measuring the γ-ray production cross sections to states not easily resolved in neutron spectroscopy. All measurements have been completed at the University of Kentucky Accelerator Laboratory using a 7-MV Model CN Van de Graaff accelerator, along with the neutron production and neutron and γ-ray detection systems located there. Students participate in accelerator operation, experimental setup, data acquisition, and data analyses. An overview of the research program and student contributions is presented.


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*Keywords:* Undergraduate research; γ-ray spectroscopy; neutron elastic and inelastic scattering; differential scattering cross sections.

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## 1. Introduction

Science majors at the University of Dallas (UD) participate in undergraduate research to help fulfill part of the requirement for the Bachelor of Science (BS) degree. For physics and chemistry majors, one of the areas of study available for their research is experimental nuclear physics, particularly in the subareas of nuclear structure and neutron scattering. For the last several years UD students have participated in a series of ($n$,$n$), ($n$,$n'$) and ($n$,$n'\gamma$) studies to measure neutron scattering cross sections from materials that are important for the design of next-generation nuclear fission reactors (see DOE [1]) and also for data evaluation purposes as global models describing neutron scattering data are developed (see Aliberti *et al*.[2,3,4]). The purpose of these studies is to measure elastic and inelastic neutron scattering cross sections for $^{54,56}$Fe, since iron is such an important structural material in the design of nuclear fission reactors, and for $^{23}$Na, which is the coolant in the sodium-cooled fast reactor. The cross sections obtained from these measurements are important not only for reactor design considerations but also for comparison to existing global model calculations of neutron scattering cross sections available at online data bases, such as the Evaluated Nuclear Data File (ENDF) maintained at the National Nuclear Data Center at Brookhaven National Laboratory (see Chadwick [5]). All the measurements are conducted away from the UD campus at the University of Kentucky Accelerator Laboratory (UKAL).

The 7 MV modified Model CN Van de Graaff accelerator located at UKAL has been used almost continuously for graduate and undergraduate student education since 1963 as part of a larger nuclear science research program that includes investigations of important questions in nuclear structure, nuclear astrophysics, neutron scattering, and applied nuclear science. UKAL is considered a university-based laboratory, but because of its ability to produce nearly mono-energetic fluences of neutrons for scattering and reaction studies, the laboratory has become in many respects a user facility. Students and faculty from UD, the United States Naval Academy (USNA), and UK have worked collaboratively for many years in both nuclear structure and neutron scattering studies. Over thirty UD students have completed their undergraduate research at UKAL - a facility that is very amenable to teaching undergraduates since they can participate in all components of the experiment from accelerator operation and repair, detector and electronic setup and operation, and data acquisition and analysis.

## 2. Experimental Apparatus

### *2.1. University of Dallas Facilities for Nuclear Physics*

The UD nuclear physics experimental facilities have no in-house neutron production capabilities. Students do have available NaI scintillation detectors and electronic equipment for singles and coincidence spectroscopy. Most of this equipment became available with a generous donation by UD alumnus Ed Stanley. This equipment is shown in Fig. 1 being used by 2015 senior Laura Aumen. The experimental research completed for undergraduate theses is performed at UKAL because of the limited nature of in-house facilities at UD.


Figure 1. Nuclear spectroscopy equipment at the University of Dallas.

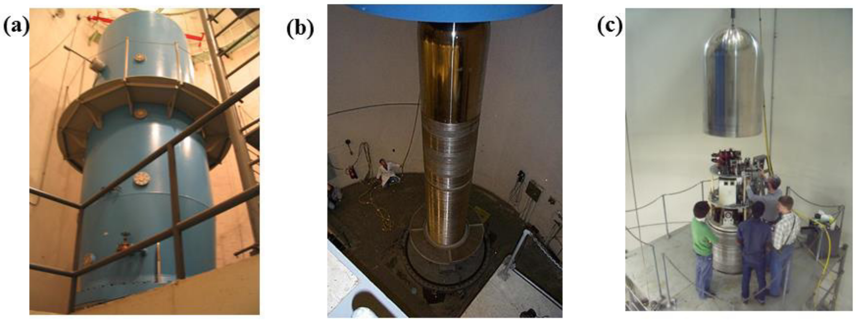


Figure 2. The 7 MV modified Model CN Van de Graaff located at UKAL shown in (a) operating condition with the tank closed, (b) with the tank lifted, and (c) with the terminal open during servicing. Two UD students, Aaron French and Zack Santonil are shown in (c), along with UK graduate student Erin Peters.

### *2.2. Facilities and Experiments at the University of Kentucky Accelerator Laboratory*

The UKAL accelerator is shown in Fig. 2 in operation and with both the tank and terminal lifted during routine accelerator maintenance. Both continuous and pulsed-bunched charged particle beams are available. The proton beams used in these studies were bunched to a FWHM of $\Delta t \approx 1$ ns. This time spread was necessary for the time-of-flight (TOF) measurements to detect the scattered neutrons. Neutrons were produced via the $^3$H($p$,$n$)$^3$He reaction. The proton beam enters the gas cell from the left in Fig. 3.The scattering samples, $^{54,nat}$Fe, were hung in air about 7 cm from the center of the gas cell and the detector and shielding apparatus rotate about a pivot point located below the center of the scattering sample, as shown in Fig. 3.

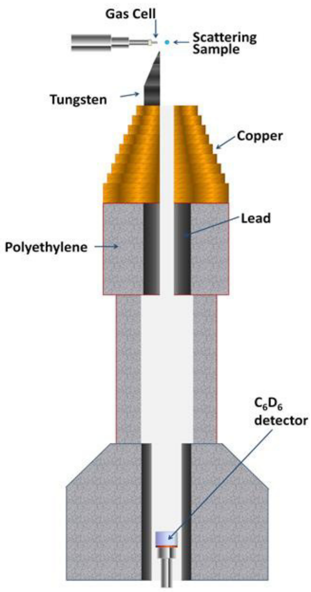


Figure 3. The gas cell, scattering sample, detector shielding, and the $C_6D_6$ neutron detector are shown in this schematic diagram from Peters [6]. The schematic diagram shown is for neutron detection experiments. For $\gamma$-ray detection measurements, the High Purity Germanium detector is placed in the shielding apparatus with both polyethylene and lead labels. The beamline, gas cell, and copper shielding remain the same.

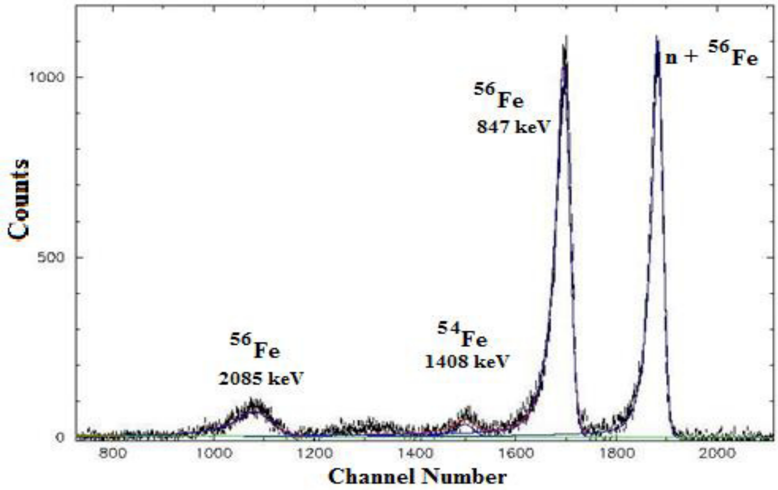


Figure 4. Neutron scattering TOF spectrum of n + $^{nat}$Fe at $E_n$ =3.19 MeV. Inelastic scattering from both $^{54}$Fe and $^{56}$Fe can be seen in this figure.

The copper and first polyethylene segments of the shielding apparatus are configured the same for both neutron and γ-ray detection. The long narrow sections of polyethylene are removed for γ-ray experiments and an HPGe detector with a BGO Compton suppression annulus is placed in the polyethylene segment adjacent to the copper section; a $C_6D_6$ liquid scintillation detector is utilized for the neutron detection measurements as shown in Fig. 3. Pulse-shape discrimination is used to eliminate unwanted γ-ray background in the neutron measurements and TOF is used to reduce neutron events in the γ-ray measurements. An additional neutron scintillation detector is used for relative normalization purposes; it is kept at a fixed location in the laboratory and counts the neutron fluence directly from the gas cell. A neutron TOF spectrum is shown in Fig. 4 and a γ-ray spectrum can be seen in Fig. 5.

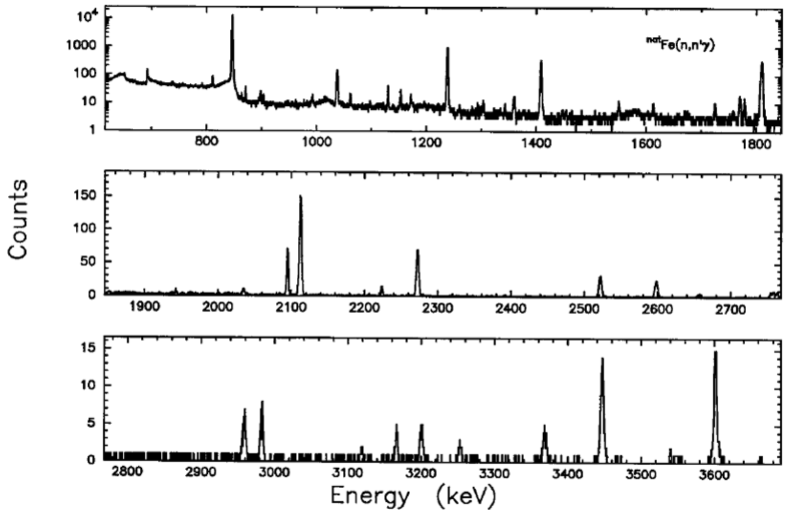


Figure 5. $^{nat}$Fe summed γ-ray excitation function data for $E_n$ = 1.5 - 4.7 MeV. The resolution is approximately 2 keV..

## 3. Student Participation and Results

### *3.1. Student Project Requirements*

Physics majors at UD must complete an undergraduate research project, write a senior research thesis, and give a presentation at a professional meeting in order to obtain a BS degree. Students who complete their required research by participating in the Nuclear Energy Universities Program (NEUP) neutron scattering program participate in experiments at UKAL and analyze the detector energy calibration and/or efficiency calibration and neutron scattering data or γ-ray detection data from at least one measurement. For neutron scattering measurements, students typically analyze detector efficiency data and two angular distributions, while for γ-ray studies they typically look at a combination of determining the detector efficiency and energy calibration and the analysis of one or more angular distributions or excitation functions across a 2- 4 MeV range of incident neutron energies. At UKAL students are able to participate in all components of the research from running the accelerator, setting up detectors, shielding, and electronics, and acquiring data. Most of the data analysis is completed at UD. Some results from student analyses are shown below in Sections 3.2-3.4 for detector efficiencies, neutron scattering, and γ-ray excitation functions; student project titles for 2010-2014 are given in Table 1.

| Student | Project Year | Project Title |
|---|---|---|
| P. McDonough | 2010 | Testing Procedures and Detectors for Neutron Elastic and Inelastic Scattering Measurements |
| L. Kersting | 2010 | Elastic and Inelastic Neutron Scattering Studies of $^{Nat}Fe$ and $^{23}Na$ at En= 3.57 MeV and 3.86 MeV |
| C. Lueck | 2010 | Fitting Neutron TOF Spectra With Multiple Neutron Groups |
| A. Sigillito | 2011 | Neutron Scattering Measurements on $^{23}Na$ and Normalization Tests |
| J. Schniederjan | 2011 | Fe-56 γ-ray Production Cross Sections from 1.5 to 4.0 MeV |
| J. Girgis | 2011 | Evaluation of Background Produced by the T(p,n)$^{3}$He Reaction in Neutron-Detector Efficiency Measurements |
| L. Downes | 2011 | Na-23 γ-ray Production Cross Sections from 1.5 to 4.0 MeV |
| B. Combs | 2012 | Neutron Scattering Measurements on $^{23}Na$ at $E_n$=3.20 and 3.57 MeV |
| L. Sidwell | 2012, 2013 | Neutron Scattering Measurements on $^{23}Na$ at $E_n$=3.20 and 3.40 MeV |
| S. Henderson | 2013 | $^{54}Fe$ Neutron Scattering Differential Cross Sections at $E_n$=3.0 and 4.0 MeV |
| A. French | 2014 | Neutron Scattering Cross Sections Deduced from $^{54}Fe(n,n'\gamma)$ |
| Z. Santonil | 2014 | Neutron Scattering Cross Sections Deduced from $^{56}Fe(n,n'\gamma)$ |
| T. Howard | 2014 | $^{54}Fe(n,n'\gamma)$ – angular distributions and lifetimes |
| L.Pecha | 2014 | $^{56}Fe(n,n'\gamma)$ – angular distributions and lifetimes |

### *3.2. Neutron Scattering Differential Cross Sections*

Neutron scattering differential cross sections are determined from the equation,

$$\frac{d\sigma}{d\Omega} = \frac{N_{abs} Y_{main}}{Y_{mon} Eff(E_n)}, \tag{1}$$

where $N_{abs}$ is the absolute normalization factor, $Y_{main}$ is the yield from the main detector, $Y_{mon}$ is the forward monitor yield, and *Eff*($E_n$) is the efficiency of the main detector at neutron energy $E_n$. The absolute normalization factor $N_{abs}$ is determined by measuring the *np* differential scattering cross sections; these cross sections are known to better than 1%. The neutron efficiency spectrum is measured *in situ* for each $E_n$ and is obtained by measuring an angular distribution of the neutrons produced in the source reaction.

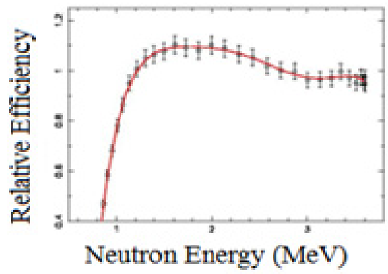


Figure 6. Neutron detector efficiency spectrum. The solid curve is a polynomial fit to the efficiency data. It is only necessary to know the detection efficiency at one energy relative to that at another for these measurements.

An example of an efficiency spectrum is shown in Fig. 6. Students analyze the efficiency data to obtain the relative detector efficiency $Eff(E_n)$:

$$Eff\,(E_n) = \frac{Y_{main}}{Y_{mon}\sigma_{^3H(p,n)^3He}}, \tag{2}$$

where $Y_{main}$ is the main detector yield, $Y_{mon}$ is the monitor yield, and σ is the know $^3$H($p,n$)$^3$He source reaction cross section. These factors are combined in Eq. 1 to give the elastic and inelastic neutron scattering differential cross sections. Angular distributions for neutron elastic scattering for $^{nat}$Fe and neutron inelastic scattering for the 847-keV level of $^{54}$Fe at $E_n$ = 3.19 MeV are shown in Fig. 7. These data were analyzed by UD students during the summer of 2013.

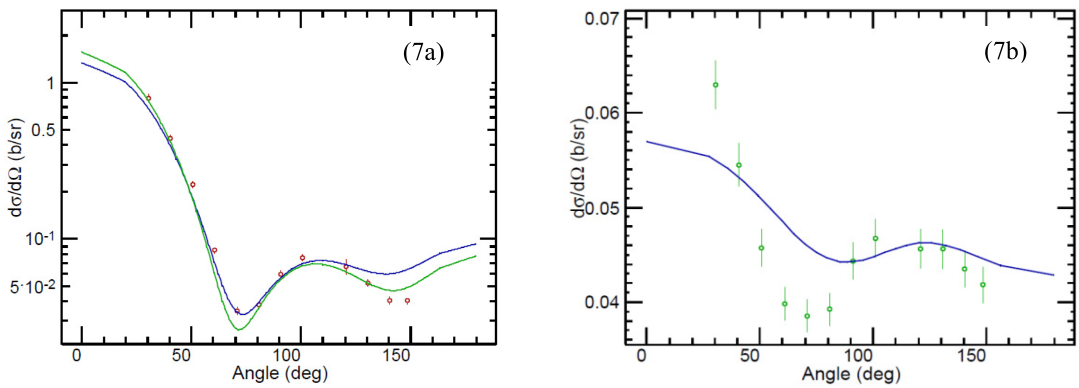


Figure 7. Neutron elastic scattering differential cross sections for $^{nat}$Fe at $E_n$ = 3.19 MeV (7a) and neutron inelastic scattering angular distributions for the 847-keV level of $^{56}$Fe at $E_n$ = 3.19 MeV (7b. The blue and green solid lines are model calculations from ENDF. While the elastic cross sections are well described by the model calculations, the inelastic scattering cross sections are not, especially at forward angles. The inelastic neutron scattering cross sections are very sensitive to the relative strengths of the compound and direct reaction components of the neutron scattering and serve as a stringent test of the models.

### 3.3. γ-ray Excitation Functions and Production Cross Sections

Students helped measure γ-ray excitation functions and completed the preliminary analysis of these data to deduce neutron cross sections for the excitation of levels unresolved in neutron scattering. The production cross section for a γ ray observed when a nucleus decays to a lower-lying excited state is found by determining the area under the angular distribution. The angular distribution $d\sigma/d\Omega$ can be described by a Legendre polynomial expansion of the form

$$\frac{d\sigma}{d\Omega} = A_0\left[1 + a_2 P_2 + a_4 P_4\right] \tag{3}$$

where

$$\sigma = \int \frac{d\sigma}{d\Omega} d\Omega = 4\pi A_o \tag{4}$$

The quantities $P_2$ and $P_4$ are second and fourth order Legendre polynomials, respectively, and $A_o$, $a_2$, and $a_4$ are the coefficients determined from the fitting process, and σ is the production cross section for the observed γ-ray. Terms higher than 4th order are not observed for the dipole and quadrupole transitions observed in these measurements, and $a_4 \approx 0$ for most γ-ray angular distributions. Excitation functions were measured from $E_n$ = 1.5 – 4.7 MeV with the detector fixed at 125° where $P_2 \approx 0$; thus, a direct measurement of $A_0$ is obtained and the angle integrated cross section is found by Eq. 4. Once these γ-ray production cross sections are determined for all γ-rays emitted from the de-excitation of level *k* or from feeding into level *k*, the neutron cross section for the excitation of the level can be deduced from Eq. 5.

$$\sigma_{n,n'_k} = \sum \sigma_{de-excitation} - \sum \sigma_{feeding\ transitions} \tag{5}$$

A γ-ray angular distribution was measured at $E_n$ = 4.5 MeV to evaluate the decay characteristics of the excited levels and to check the validity of the $a_4 \approx 0$ assumption. Level lifetimes in the few femtosecond to few picosecond range will be ascertained from these data using the Dopper-shift attenuation method. Student projects for summer 2014 included the analyses of these angular distribution data. An excitation function for an observed 2756-keV γ-ray in $^{nat}$Fe is shown in Fig. 8. The analysis of these data continues.

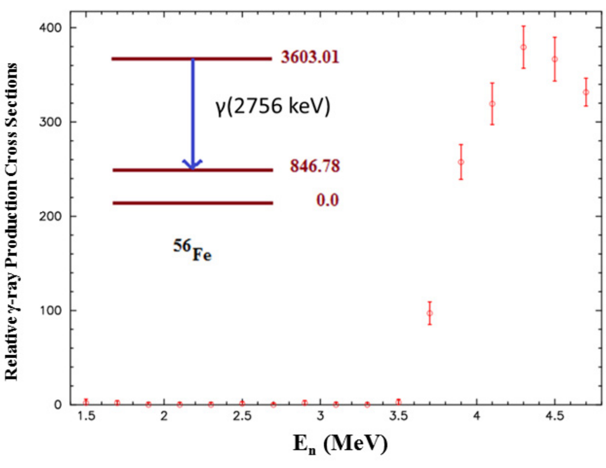


Figure 8. Relative production cross sections for the observed 2756-keV γ ray in $^{56}$Fe.

## 4. Conclusions

University of Dallas undergraduate students completed research projects to investigate neutron elastic and inelastic scattering cross sections frorn $^{54,56}Fe$ which are important for fission reactor applications and for testing global model calculations for these nuclei. Both neutron and γ-ray detection are important for understanding neutron scattering. While the former is a direct measure of neutron scattering differential cross sections, the latter is important for deducing neutron scattering probabilities to closely spaced excited levels.

Students learn about accelerator operation, neutron and γ-ray detection, data acquisition and analysis, and nuclear physics of the scattering and nuclear de-excitation processes. These projects become the subjects of their undergraduate theses and conference talks. Many of these students continue to graduate programs in either physics or engineering. The use of accelerator facilities at UKAL has been very valuable in the education and career choices of many UD undergraduate students for over two decades. The hands-on experimental nuclear physics offered there is ideal for undergraduate education.

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